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A NEW APPROACH FOR EVALUATING THE STROMBOLIAN TYPE ACTIVITY

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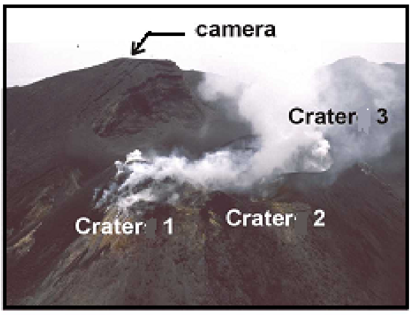
Introduction

Volcanoes represent one of the most important application fields for risk mitigation techniques (Mc Guire, Kilburn, and Murray, Eds, 1995) due to the ingent damages and casuality. This paper deals with a monitoring system that could be successful used for risk mitigation related to forecast paroxysmal explosions of strombolian type.
The typical activity of Stromboli volcano consists of intermittent mid explosions lasting a few seconds, which take place at different vents and at variable intervals, the most common time interval being 10-20 minutes (Chouet, Hamisevicz, and McGetchin, 1974; Blackburn, Wilson, and Sparks, 1976). However the routine activity can be interrupted by more violent paroxysmal explosions, that eject m-sized scoriaceous bombs and lava blocks to a distance of several hundreds of meters from active vents. On average, one or two paroxysmal explosions occurred per year over the past century, buth this statistic may be underestimated in absence of continuous monitoring. For this reason from summer 1996 a remote surveillance camera works on Stromboli recording continuously the volcanic activity. It is located on Pizzo Sopra la Fossa, 100 metres above the crater terrace where are the active vents (Fig. 1a).



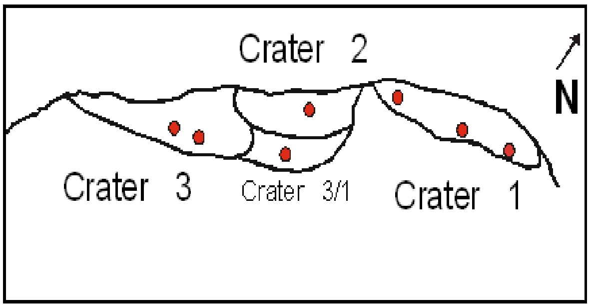


Figure 1. a) (left) Stromboli crater area and indication of the Pizzo Sopra la Fossa area where the camera is located; b) (right) Schematic representation of the crater area as seen form the camera.

Moreover, from September 2001 an on-line image analyzer system referred to as VAMOS (**V**olcanic **A**ctivity **MO**nitoring **S**ystem) operates detection and classification of explosive vents in real-time. Using VAMOS it is possible to identify changes in the explosive activity trend that could precede a particular eruptive event, like paroxysmal explosions, fire fountains, lava flows. Since the camera installation up to present, several explosions occurred at the different craters and the parameterization in classes of intensity for each explosion on the base of tephra dispersion and kinetic energy have been made. The analysis include the counting of the explosions occurred at the different craters and the parameterisation in classes of intensity for each explosion on the base of tephra dispersion and, in generic sense, of the kinetic energy released. The plot of dissipated energy by each crater versus time seems to exhibit a cyclic behaviour with max and min explosive activity ranging from a few days to a month. Often the craters show opposite trends so when the activity decreases in a crater, increases in the other. Before every paroxismal explosion recorded, the crater that produced the event decreased and then stopped its activity from a few days to weeks before. The other crater tried to compensate increasing its activity and when it declined the paroxysmal explosion occurred suddenly at the former site (Coltelli, and Cristaldi, 2003). The system has automatically recorded and analysed the change in energetic trend that proceded the 20 October 2001 paroxysmal explosion that killed a woman and the strong explosive activity that preceded the onset of 28 December 2002 lava flow eruption.

The VAMOS System

The VAMOS system, developed at INGV (Istituto Nazionale di Geofisica e Vulcanologia) in Catania, is based on a previous study presented by Bertucco and others (1999). This software allows on-line detection and analysis of images recorded by the camera positioned on the summit of Stromboli volcano. Images are sent to a central recording station at INGV monitoring centre located in Catania (Sicily) and then processed by a computer system equipped with a IMAQ analog image acquisition devices from National Instruments. The recording and event detection algorithms has been implemented in the framework of the LabVIEW software.

VAMOS can process images consisting of 640x480 pixels at a maximum rate of 5 frames per second that is considered acceptable for the purposes of the system. The core of the monitoring system is the so-called *trigger* i.e. the algorithm developed for detection of explosive events. The trigger works as follows. Let us indicate by frame(n) and frame(n+1) two consecutive frames recorded by the camera. These images are preliminary pre-processed by applying an appropriate threshold algorithm whose purpose is that of obtaining images with black and white pixel only.

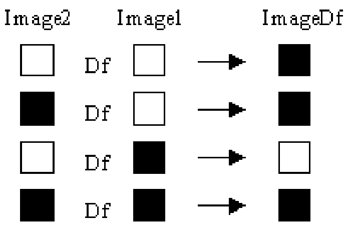


Figure 2. Rules to obtain the ImageDF

The two images are subsequently *subtracted* pixel by pixel following the rules shown in Figure 2 in order to obtain the difference between images (ImageDF). The white pixel in ImageDf represent areas were ejected products are possibly located. However in order to decide if an explosion event is detected the number N_{pix} of white pixels in the ImageDf is compared with a threshold value S^*. If $N_{pix} > S^*$ then an explosive event is detected and the frames are stored in the hard disk for further analysis. Then the overall process is repeated until an ImageDf characterized by $N_{pix} < S^*$ is detected. The condition $N_{pix} < S^*$ means that the final frame of the detected event has been reached. The S^* value depends on several conditions and is tuned by a trial and error approach. An example of event detection is shown in Figure 3.

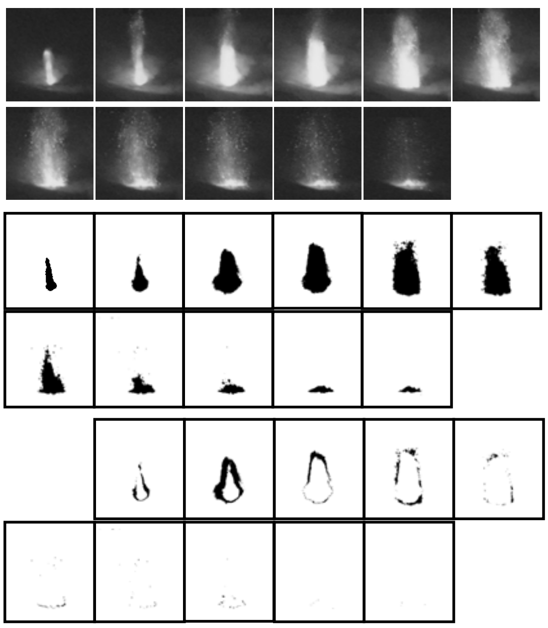
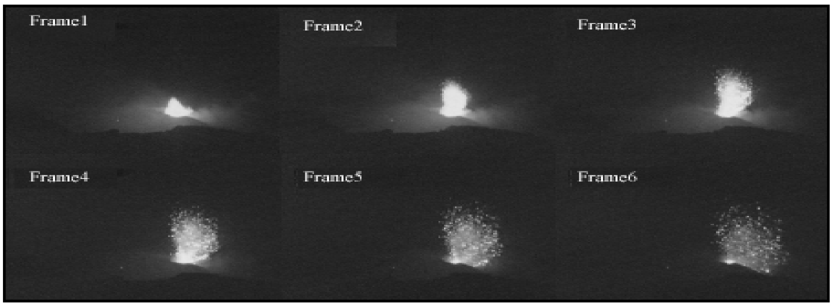


Figure 3. a) original sequence; b) intermediated (after the threshold); c) final sequence (ImageDf)

The efficiency of the trigger has been assessed by comparing the number of events occurred during June-August 1996 and August – September 2000 with the number of events recognized by an expert human operator. The statistic computed on 379 events occurred on 1996 and 1080 occurred on 2000, show that the number of event correctly detected range from 88% to 100% depending on the explosion type (wide or narrow burst pattern, see the following paragraph).

Once an explosion has been detected by the trigger all the frames that represent are *summarized* into a final image, that will be referred as ImageMax, that allows to visualize the overall area interested by the event (Fig. 4)
One of the main aims of synthesizing information about an explosive event into ImageMax is that it allow to compute the width a length of the area interested by the event.



(a)

(b)

Figure 4. a) frames of ImageDf type; b) corresponding ImageMax

Classification of Explosive Events at Stromboli

Based on studies mainly carried out during the last decade explosion events recorded at Stromboli can be roughly classified into two main classes: a) single events and b) multiple events or sequences. Events belonging to the first class are characterised by very short duration, on average from 5 to 15 seconds. This type of event are "impulsive" and represents the classic strombolian type explosions. The second class is represented by sequences of events that can be sometime very different each others (e.g. lava fountain, strombolian or vulcanian blast, small eruptive column) spanning in time from some tens of seconds to some minutes. Events belonging to both the classes produce pyroclastic deposit falling in the field of typical strombolian eruptions characterised by a limited dispersion range and a low degree of fragmentation of the ejected materials as recognised by Walker, (1973), and by Cas, and Wright, (1987).
Energy released during the strombolian activity, that is basically a blast or a series of blasts, can be partitioned in many different forms (mainly kinetic, thermal and elastic), however during explosive activity kinetic energy dissipated by the particle during its ballistic paths is preponderant (Shimozuro, 1968; Chouet, Hamisevicz, and McGetchin, 1974; Blackburn, Wilson, and Sparks, 1976; Ripepe, Rossi, and Saccorotti, 1993).
Based on systematic observations of the activity at Stromboli, carried out by means of the camera mentioned above, in this paper more detailed classification are possible. Coltelli, and Cristaldi, (2003) tried to analyse images from surveillance camera since 1996 finding that explosive activity vary significantly during the time as intensity, style and occurrence (different craters) with days and, sometime, hours rate. Moreover before some paroxysmal explosions recorded, the crater that produced the event decreased its explosive activity and then stopped from a few days to weeks before, whereas the other craters tried to compensate increasing its activity and when it declined the paroxysmal explosion occurred suddenly at the former site. Even if these paths are not confirmed yet by a sufficient number of case of study, we started the investigation in the computation of energy released during the strombolian activity using the images continuously recorded by the remote surveillance camera operating at Stromboli volcano.
Thanks to the introduction (below in the text) of an appropriate strategy for evaluating the energy involved with the Stromboli volcanic activity a systematic study of the precursor of the major event is now possible. In more detail in this paper explosive events occurring at Stromboli are classified into six classes according to the following criteria. Based on the ratio R between the height (h) and the width (w) of the event trace impressed in the ImageMax, explosive events are classified into two classes based on their burst pattern, referred as *narrow (N),* if $R>R^*$, and *wide (W),* respectively, R^* being an appropriate threshold value of the ratio R. A further classification adopted in the present study consists into discriminating events based on the maximum altitude reached by ejected material that is related to the volcanic particles with the maximum (muzzle) velocity at the vent. To this end three classes of altitude are considered, referred to as 1, 2 or 3 respectively, corresponding to a maximum altitude reached by the ejected products of 75, 140 and 200 (or more) meters (Fig. 5).

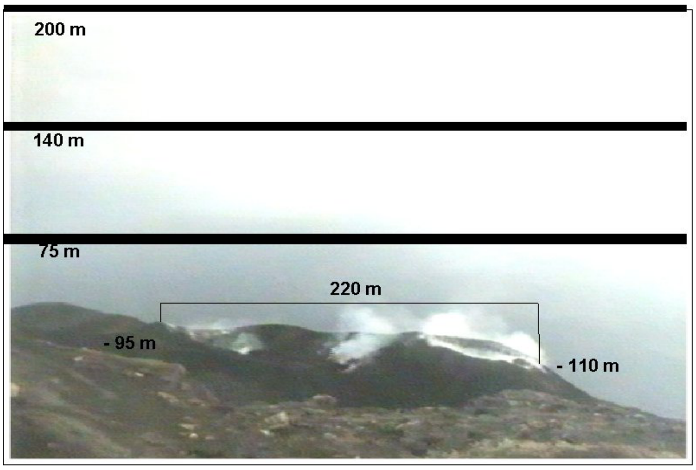


Figure 5. camera view of the Stromboli's crater terrace

Finally the system is able to automatically recognize which one of the three craters existing in the Stromboli summit area is responsible for a given event.
Summarizing, for each individual crater, events can be classified into six classes referred to as *Ni* and *Wi* (*i=1,2,3)*. Here *N* and *W* stands for Narrow and Wide respectively while (*i=1,2,3)* represents the three different altitude reached by ejected materials.
Based on the fact that the maximum altitude reached by the ejected products and the size of the area involved represent an indirect measure of the energy involved we conjecture that the six recognized sets can be ordered in terms of increasing energy as follows:N1< W1<N2<W2<N3<W3.
Based on this conjecture, in this work it is proposed to heuristically associate an index, referred as I_E representing an indirect measure of the energy involved to the events belonging to each of the six considered classes. The conventional index of energy chosen are shown in Table 1.

Class	Index of Energy (I_E)
N1	1
W1	1.4
N2	2
W2	2.7
N3	3
W3	5.1

Table 1 – Class of events and associated index of Energy

Now it is straightforward to use I_E in order to compute an heuristic value of the Average Daily Energy Released during the explosive activity at Stromboli as follows

$$ADER = \frac{1}{n_h}\sum_{i=1}^{n} I_{E_i}$$

where n_h is the total number of hours analysed during a day, *n* is the number of events detected during a day and I_{Ei} the conventional energy associated with the i-th event. The considered time period n_h ranges from 8 to 10 hours in which darkness allows to recognize the glowing ejected fragments, that generally consist of partially molten volcanic bombs. Another limitation is due to the presence of hydro-meteoric or volcanic clouds above the vents, this reduced the observation period also in the darkness; in fact we reject data from a period lasting less than 4 continual hours because is not statistically significantly of the eruptive activity in the day considered. However these shortcomings will be removed soon by using a camera sensible to mid-infrared region of the spectrum in which only hot bodies are visible with almost the same intensity in every light condition. By plotting the introduced ADER quantity it is possible to obtain figures such as Figure 6 and Figure 7.

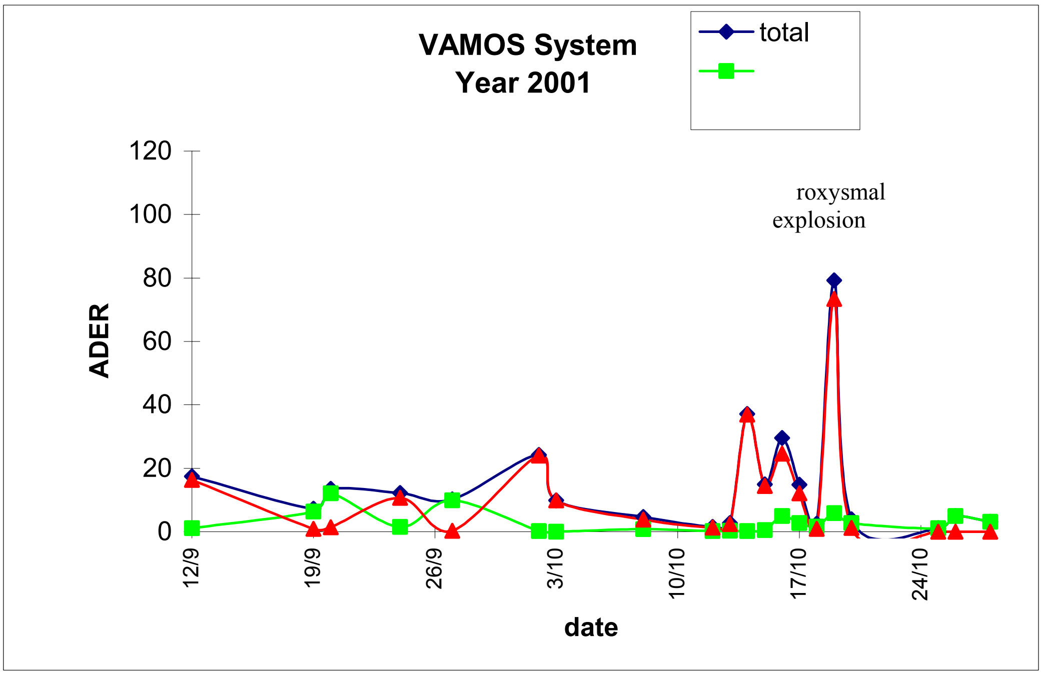


Figure 6. Explosive energy recorded from September 12 to October 28, 2001.
(Note: the value of the paroxysmal event is only indicative)

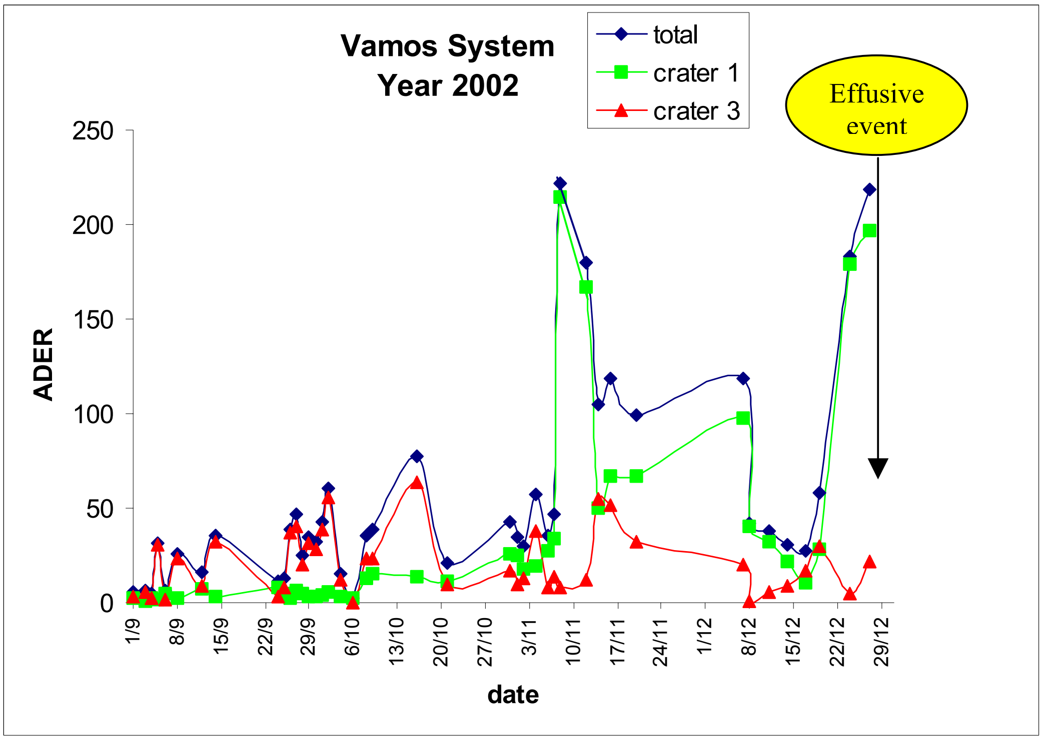


Figure 7. Explosive energy recorded from September 1 to December 27, 2002

In these figures it is possible to recognize some common behaviour immediately before paroxysmal events, as discussed by Coltelli, and Cristaldi, (2003). In more detail from Figure 6 it is possible to see that the evaluated energy exhibits an oscillating behaviour starting from September 12. At the beginning of October, 2001 the activity at crater 1 ceased while at crater 3 an intense activity was observed with peaks at the nights between 2 and 3 October, 14 and 15 October and 16 and 17 October. Then a suddenly decrease of the activity observed at crater 3 preceded the paroxysmal event recorded on October 20, 2001. In Figure 7 it is shown that during the period from September 1 to October 20, 2002, the typical oscillating behavior was observed at the crater 3 while the activity at the crater 1 was very low, moreover the ADER value grew of 2-3 time from its typical average value of 20 observed during the normal strombolian activity since 1996. At the beginning of November 2002, a suddenly increasing of the explosive activity at the crater 1 was observed reaching it maximum of 221 on November 8, exceeding by a factor 11 its normal value. Then activity at this crater gradually vanish, until on December 24 when suddenly increased again up to 218, heralding the ongoing lava flow eruption, started on December 28, that probably is the largest eruption of Stromboli in the last century.
In summary both the episodes described show as the trend of ADER value could be used as early warning of dangerous paroxysmal explosive events and in general of the strongest eruptive activity at Stromboli, inferring that energy dissipated by mild strombolian explosions could be considered as a "regulator" of the volcano shallow plumbing system.

Conclusions

In this paper a new approach to heuristically evaluate the energy released during the explosive activity at Stromboli was proposed. The approach is based on a classification of explosive events that this volcano produces, based on the maximum altitude and dispersal (area covered in the image) of the ejected material. Although the introduced index does not represent the actual magnitude of the kinetics energy released during explosive activity, it seems that by plotting the Average Daily Energy Released (ADER) it is possible to characterize the explosive behaviour of the individual craters and to warn the incoming major changes in their activity. Such a kind of plots represent an interesting synthesis of the explosive history of each crater and provided that a sufficient large record of data will be available, we expected that precursors of the paroxysmal explosions will be recognised in future.

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